NISTIR 6288

NIST Workshop on Standards Development for the Use of Fiber Reinforced Polymers for the Rehabilitation of Concrete and Masonry Structures, January 7-8, 1998, Tucson, Arizona. Proceedings

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Dat Duthinh[1]

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[1]Structures Division
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NIST

United States Department of Commerce
Technology Administration
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Typical Manufacturing Flaws in FRP Retrofit Applications

by Gary F. Hawkins, Eric Johnson and James Nokes
The Aerospace Corporation

FRP materials are being used to retrofit columns and rehabilitate concrete structures. There are three different manufacturing methods for applying FRP to concrete. Each method has the potential for creating debonds at the FRP-concrete interface and within the FRP itself. Thermography is a nondestructive evaluation technique which can image debonds below the surface of an FRP. Thermography was performed on columns which had been wrapped with FRP using three different methods to determine the size and frequency of debonding characteristic of that manufacturing method.

The results indicated that hand lay-up methods leave hand sized air bubbles at the concrete composite interface. Pre-cured shells leave large debonds in areas where the shells are not adequately secured during the cure of the adhesive. Machine wrap methods do not leave debonds on circular columns but may leave large debonds on rectangular columns if the flat side of the column is slightly concave. A discussion is also presented concerning the acceptable size of flaws in these applications.

Keywords: debonds, flaws, FRP, nondestructive evaluation, repair, stiffening, strengthening,

INTRODUCTION

In December 1995, the California Department of Transportation (Caltrans) formally initiated a program for the evaluation and qualification of advanced composite materials for seismic retrofit and rehabilitation of structures. The principal initial application of composites by Caltrans is as a casing or over-wrap on bridge columns for enhancing seismic resistance. Several composite manufacturers have developed composite casing systems which have potential for being cost effective relative to current steel casing designs. In April 1996, Caltrans issued pre-qualification requirements for alternative column casings for seismic retrofit. The requirements called for each potential bidder to wrap a full-scale column as a demonstration of their capability. These columns were tested using thermography to detect flaws hidden underneath the surface of the composite. This paper summarizes the types of flaws introduced by each of the different manufacturing techniques.

Composite Manufacturing Techniques for Over-wrapping Columns

When viewed in a very broad sense, there are three primary methods for over-wrapping columns: hand lay-up, pre-cured shells, and machine wraps. Each method has its own difficulties which result in the introduction of debonds which are unique to the type of manufacturing method. The methods are described below.

1) Hand Lay-Up

The hand lay-up system involves placing the uncured fabric on the column by hand. The fabric normally comes in wide rolls and is cut to a length that can be conveniently handled. The wide fabrics are normally infiltrated with liquid resin by dipping the cut length in a bath which is located near the base of the column. The tacky, and possibly dripping, fabric is laid onto the column and spread by hand to smooth the fabric and release any trapped air.

A separate hand lay-up technique is very similar to wallpapering a wall. In this case, the fabric comes in 25 cm wide rolls with a paper backing. The resin is applied to the column using a traditional paint roller. The fabric is laid onto the column over the resin and smoothed by hand. The backing paper is removed and another coat of resin is applied directly on the fabric. The resin wicks into the fabric from both sides and is intended to fully infiltrate the fabric. In both cases the systems are allowed to cure at room temperature.

2) Pre-cured shells

In this method, shells with the same diameter as the column are manufactured in a factory environment. The shells are slit longitudinally so the shells can be opened wider than the diameter of the column. The shells are trucked to the job site for mounting on the column. After cleaning and preparing the column, the column is sprayed with adhesive in the area where the shell will be attached. The shell is opened along the split line either by hand or with the aid of a support. The shell is then slipped around the column. After releasing it from the support, the shell returns to its original shape and snaps onto the column. To build up the over-wrap to the proper thickness, this process is repeated by spraying adhesive on the mounted shell and snapping on additional shells. To reach the proper height, additional shells are butted up against each other vertically.

The shells are oriented such that the split lines never line up. For example, if four shells are required to make the proper thickness, the split lines would be located at 90 degree increments around the column. The location of the butt ends between the top of one shell and the bottom of the next are also staggered so any particular section contains, at most, one butt end through its thickness.

After all of the shells are on the column, cinching straps are tightened over the shells to squeeze out any excess adhesive and tighten the shells onto the column.

3) Machine Wrap

Two of the manufacturers use a machine to wrap the fibers directly from a spool onto the column. The matrix material has either been pre-impregnated into the fibers on the spool or the fibers are impregnated by dipping them into an epoxy bath just before they are wrapped onto the column.

The machines are constructed at the job site and are in the form of a circular track around the column. The machine is typically hung from chains which have been attached to the underside of the bridge. The spools of fiber and the epoxy bath rotate around the column following the circular track. The machine climbs up the chains and wraps the column with fibers.

THE THERMOGRAPHIC TECHNIQUE

Thermography is an established nondestructive evaluation technique for many materials. It is particularly well suited to the detection of the debonds and delaminations commonly found in composite structures. Thermography utilizes the effect these defects have on the thermal conduction characteristics of the material. The region containing a debond or delamination has a decreased thermal conductivity. Consequently, after heat is momentarily applied to the outside of the structure, the flawed areas cool more slowly (stay hot longer) than normal areas. An infrared camera images the temperature of the area and the flaws show up as hot spots on a cool background.

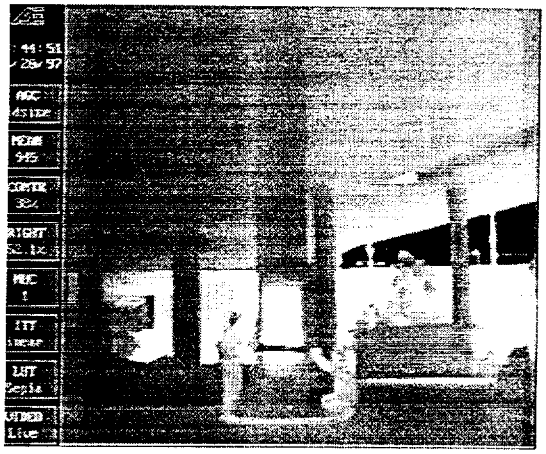

Figure 1. Infrared image of a column being heated.

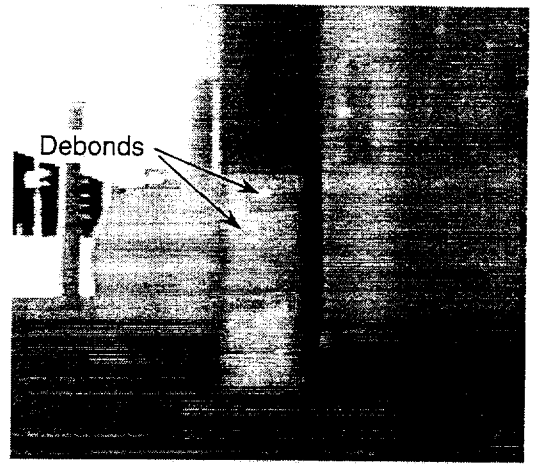

Figure 2. Infrared image of column 15 seconds after heating. Hand lay-up technique was used to apply FRP.

Figure 1 is the image of a column taken from an infrared camera. The two technicians in the scene are slowly lowering a heat source. The heat source consists of 12 quartz lamps (500 W/lamp) mounted on a semicircular frame. The frame has wheels that hold the lamps 10 cm away from the column. In these experiments, the heat source was rolled down the column a distance of 2 meters in 30 seconds. The surface temperature of the composite over-wrap never exceeded 40 degrees centigrade. This temperature cannot cause damage to the composite, yet readily exposes the debonds. Notice in the figure how the area above the heat source is hotter (shown as a lighter shade) then the unexposed areas below the heat source. After the heating is complete, the heat source is moved out of the scene and after a few seconds an image, such as in figure 2, is displayed by the infrared camera. The hot areas which correspond to debonds are displayed as a lighter color; consequently, it is quite easy to detect the debonds from these images.

The image of the debond takes a few seconds to "develop." This is the time required for the heat to flow through the material to the debond. At that time, the heat essentially stops flowing though the material because it is impeded by the debond. In normal areas the heat continues flowing into the concrete. The image of this debond becomes visible when the sensitivity of the infrared camera is enough to detect the temperature difference between the debonded and the normal areas.

As explained earlier, the development time is a function of the time it takes for heat to flow through the material to the debond. Consequently, analyzing the intensity of the debond image as it develops, yields information about the depth of the debond.

After it has developed, the amount of time that a debond is visible in the image is a function of the overwrap material's thermal conductivity. The image only remains visible until the heat flows from the hot area to the surrounding colder material. The heat flow rate is a function of the thermal conductivity of the material. The image in figure 2 was taken from a fiberglass shell that has a low thermal conductivity. Consequently, the image lingers for over a minute. In graphite materials the conductivity is much higher (some graphite have conductivity higher than that of copper). These images must be captured quickly before the hot areas blend into the background.

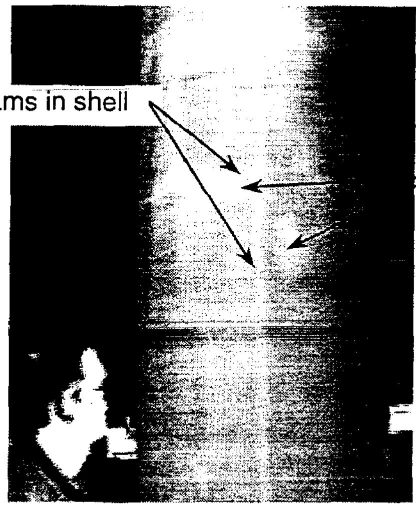

Figure 3. Debonds in a prefabricated shell.

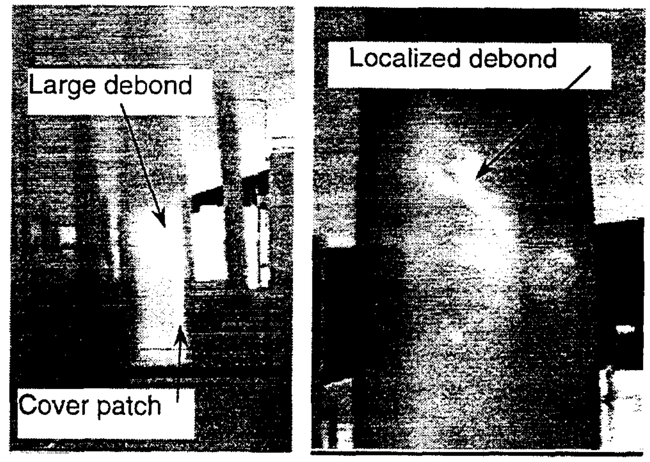

Figure 4. Large debond in a pre-fabricated shell

TYPICAL FLAWS IN COMPOSITE OVERWRAPS

Hand Lay up Debonds

Figure 2 displays typical flaws for a hand lay-up system. When the wet fabric is laid on the column it is smoothed down and can trap air pockets. These air pockets become debonds when the material is cured. These debonds are typically 10 cm in diameter and randomly distributed over the column. If the workmen had a problem in a certain area, usually a cluster of small debonds of this sort is evident.

Prefabricated Sheet Debonds

Figure 3 shows an image of some debonds in a prefabricated shell. These tend to be close to the slits or the butt ends where the cinching straps have not been effective. In some cases these can get very large.

Figure 4 shows an area with an approximately 75 cm by 25 cm debond. This can be caused by the spray-on adhesive partially curing before the straps are cinched tightly. If the shells cannot slide with respect to each other, then they cannot tighten themselves to the column and a large debond results.

Figure 5 shows a core section taken from the area indicated in figure 4. The debond thickness, or in other words, the gap between the shells was approximately 3 mm.

Machine Wrap Debonds

No debonds of any significance have been found to date on machine over-wrapped circular columns. Laying down the fibers one strand at a time precludes the formation of large debonds on circular columns. There have been large debonds noted on machine wrapped rectangular columns though.

These seem to be caused by a slight concavity in the flat surface of the column, which causes the fibers to "bridge" from one high point to another.

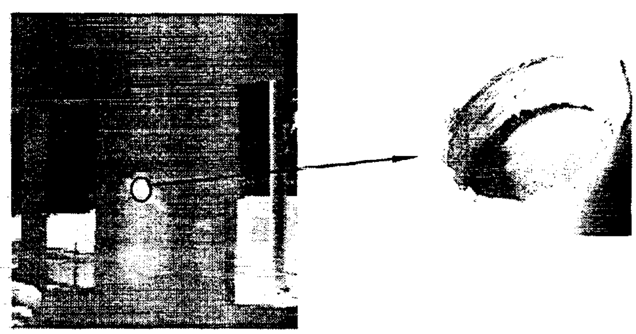

Figure 5. Core section of large debond discovered in prefabricated shell

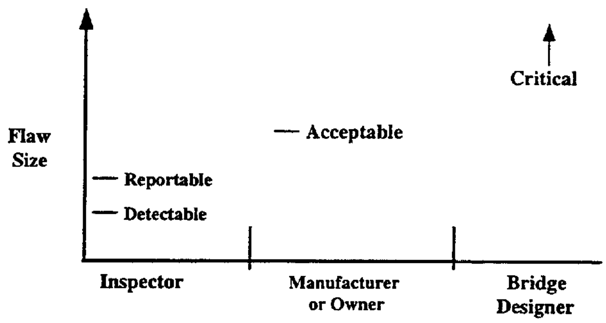

Figure 6. Notional graph indicating the size concerns of different disciplines

Acceptable Flaws

Any discussion of debonds always leads to questions about which debonds affect the performance of the structure. The question is viewed differently by three different types of people interested in the subject. The three types of people are the inspectors, the manufacturers or owners, and the bridge designers. The following discussion refers to the notional graph shown in figure 6.

The inspectors want their inspection technique to be capable of detecting all of the flaws that they need to report. Therefore, they design their equipment to detect flaws that are smaller then they need to report, which ensures they will detect all of the reportable flaws.

The manufacturer (and presumably the owner) knows that all manufacturing systems are capable of producing some flaws. These flaws are benign and inherent in the manufacturing procedure. In most cases, totally eliminating the flaws is impractical or would make the process too expensive. This is not to say that all flaws are acceptable though. If the flaws start to exceed a certain size or frequency it implies that the manufacturing procedure is getting out of control. Flaws below this size are an acceptable part of the manufacturing procedure but above this size they are unacceptable and indicative of sloppy work.

The bridge designer has a very difficult time determining the size of a flaw that is critical to the successful performance of the structure. This can only be done in a few cases where the fracture mechanics of the materials and the loading conditions are well known. To alleviate the calculation, the designer should make sure that his design is robust enough such that the acceptable flaws cannot affect the performance of the structure. That is to say, any flaw that is critical to the successful performance of the structure would have been eliminated because it was unacceptable to the manufacturer. This absolves the bridge designer from trying to calculate a critical flaw size. The designer only needs to show that flaws acceptable to the manufacturer are acceptable to him.

CONCLUSION

The three different manufacturing techniques leave different types of debonds in the final product. The large debonds must be repaired and the manufacturers should alter their process to avoid introducing them in the structure. In most cases the debonds are small and will not effect the performance of the structure. In these cases, the NDE results are used as a quality control mechanism so the manufacturer knows that the process is not out of control and the owner knows he has purchased a quality product.